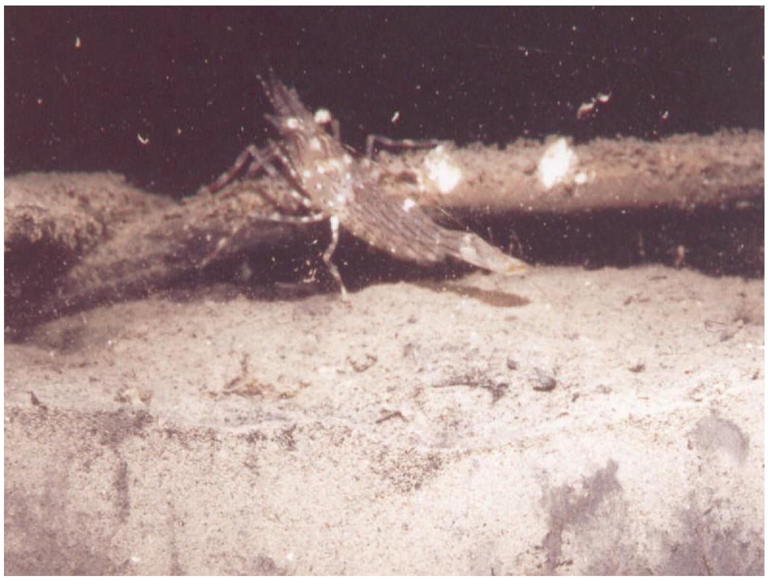
PORT ANGELES HARBOR
WOOD WASTE STUDY
PORT ANGELES, WASHINGTON

FINAL

February 5, 1999



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EXECUTIVE SUMMARY

Port Angeles Harbor, Washington has been listed as an impaired water body under the 1998 Clean Water Act 303(d) for not meeting water quality standards for dissolved oxygen. The Washington State Department of Ecology (Ecology) wants to determine the extent to which water quality problems are due to wood waste accumulation. Science Applications International Corporation (SAIC), under contract to Ecology, conducted a survey to map the extent of wood waste on the harbor bottom and assess the biological impact due to its accumulation. The study was designed to address the following objectives:

1. Map the horizontal extent of wood waste accumulations
2. Measure the thickness of the accumulations
3. Describe the wood waste encountered
4. Measure the depth of the apparent redox potential discontinuity (RPD)
5. Identify areas with potential for high sediment oxygen demand (SOD)
6. Evaluate the health of the benthic macroinvertebrate community

The survey was conducted in subtidal portions of Port Angeles Harbor (west of the end of Ediz Hook; 123° 24'W Longitude) using sediment vertical profile photography, sediment plan-view photography, and towed underwater video. The following is a summary of the major findings of this study:

- Wood waste covers approximately 25 percent (500 acres) of the bottom of Port Angeles Harbor, primarily in nearshore log booming areas.

- Five types of wood waste were identified on the bottom of Port Angeles Harbor:
  - Logs or large wood pieces
  - Small wood and/or bark chips (wood chips)
  - Very fine wood particles and/or fibers (wood pulp)
  - Trace to sparse wood pulp/chips mixed within the sediment column
  - Sparse, scattered wood pieces on top of the sediment surface

- Abundant wood debris including logs and large bark/wood fragments was observed in the active and historical log booming grounds. Large piles of recently deposited logs were observed in the active log booming grounds along the northern portion of the harbor. Size and abundance of wood debris decreased offshore from the booming grounds.

- A layer of wood pulp covering approximately 35 acres is buried under 6 to 8 cm of ambient silt in the western central harbor. The layer represents an estimated volume of 9,500 cubic yards of wood pulp (wet-volume).

- Shallow apparent redox (RPD) depths in Port Angeles Harbor were associated with active and historical log booming grounds and indicate organic overloading. Stations with very shallow to non-existent apparent redox depths were observed close to shore near the Daishowa facility, the public log dump grounds, the booming grounds near K-Ply, and the former ITT Rayonier grounds.

- Accumulation of fine wood waste (pulp) has contributed to apparent high sediment oxygen demand (SOD) conditions in the western harbor near the Daishowa and M&R Timber facilities, the public log dump, the booming grounds near K-Ply, and the former ITT Rayonier grounds. Bacterial mats, which indicate organic loading and low dissolved oxygen conditions, were also observed at four stations in the western harbor.

- Organism-Sediment Index (OSI) values in the central harbor were between +7 and +11 indicating healthy benthic infaunal communities. Stressed or disturbed communities (OSI values less than +6 were generally observed in the log booming grounds. Degraded benthic habitat (OSI less than zero) was observed in near shore areas of the western harbor (stations 8, 12, 40, 43, and 95). Such habitat is of little value to fish.

- The presence of sparse, scattered wood debris on the sediment surface (offshore of the log booming areas) appears to have minimal impact on the health of the benthic community and provides habitat for epibenthic organisms (e.g., shrimp, crabs, fish, etc).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

Port Angeles Harbor, Washington is located on the northern side of the Olympic Peninsula, along the Strait of Juan de Fuca (Figure 1). The harbor has been listed as an impaired water body under the 1998 Clean Water Act 303(d) for not meeting water quality standards for dissolved oxygen. Some areas of the harbor have been reported to be anoxic in places, lacking shellfish and bottom fish.

Logging and timber have been important industries to Port Angeles since the early 1900's. The Washington State Department of Ecology (Ecology) wants to determine the extent to which water quality problems are due to accumulations of wood debris from a history of log rafting and other sources of wood debris to the harbor (see Figure 1). Under contract to Ecology, Science Applications International Corporation (SAIC) conducted a survey to map the extent of wood waste accumulation in Port Angeles Harbor, and assess the biological impact due to its accumulation. SAIC conducted the survey in subtidal portions of Port Angeles Harbor (west of the end of Ediz Hook; 123° 24' W Longitude) using sediment vertical profile photography, sediment plan-view photography, and towed underwater video. The study was designed to address the following objectives:

1. Map the horizontal extent of wood waste accumulations
2. Measure the thickness of the accumulations
3. Describe the wood waste encountered
4. Measure the depth of the apparent redox potential discontinuity
5. Identify areas with potential for high sediment oxygen demand
6. Evaluate the health of the benthic macroinvertebrate community

This report presents the results of the wood waste study conducted in Port Angeles Harbor in November 1998. This study provides a first step in determining a Total Maximum Daily Load (TMDL) or alternative for dissolved oxygen in Port Angeles Harbor. The results will be used to guide decisions about more in-depth studies, and identify possible corrective actions or best management practices for log rafting in Port Angeles Harbor.

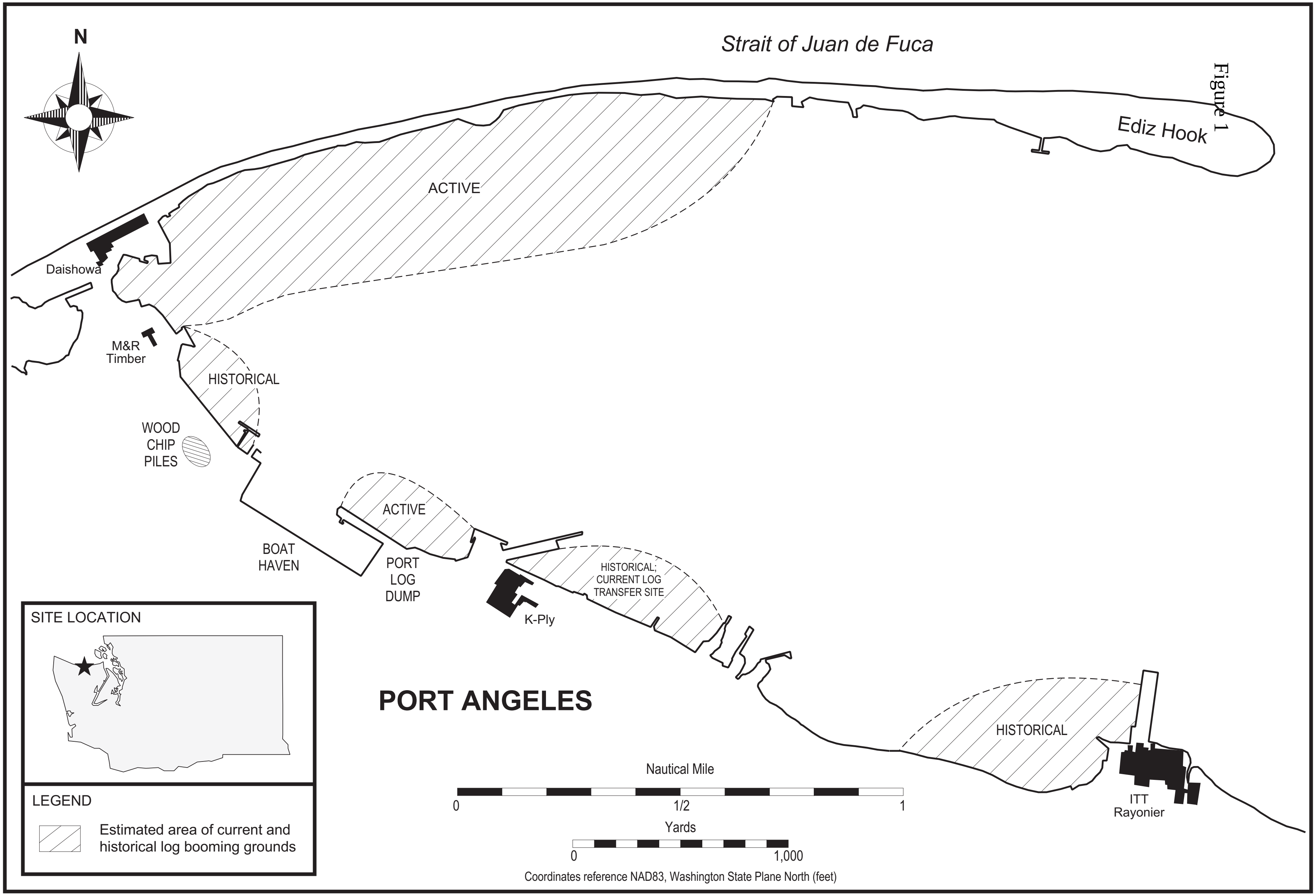


Figure 1. Port Angeles Harbor, Washington, with estimated area of current and historical log booming grounds.

2.0 FIELD METHODS

A field survey of wood waste in Port Angeles Harbor was conducted from November 3 through 6, 1998 using sediment vertical profiling system (SVPS) photography, sediment plan-view photography, and towed underwater video. Survey operations were conducted aboard the R/V BRENDAN D II, owned and operated by Sound Vessels Inc. of Port Townsend, WA. A chronological description of field sampling operations can be found in the field log (Appendix C).

2.1 Towed Underwater Video

During the first day of the study, towed underwater video was used as a reconnaissance tool in Port Angeles Harbor, to determine preliminary boundaries of wood waste accumulation. This information was used as a guide to locate the SVPS and plan-view station locations. The towed underwater video provided a real-time visual inspection of surficial features (physical and biological) on the seafloor. Large wood wastes (e.g., submerged logs) and mobile bottom fauna (e.g., fish and crustaceans) may not be photographed routinely using SVPS or plan-view photography, but can be observed using the towed video system. A total of 12 towed video transects were occupied, providing a good synoptic view of seafloor conditions in Port Angeles Harbor (Figure 2).

The towed underwater video system consisted of a SeaCam 2000 underwater camera (DeepSea Power and Light, San Diego, CA) attached to a towfish in a downward looking orientation. A 250-watt underwater light provided illumination. The video camera was oriented to view a 1-meter wide area of the seafloor. One complete set of VHS tapes containing the towed video record will be submitted to Ecology as part of the final report.

2.2 SVPS Photography

A three-day SVPS photographic survey was conducted in Port Angeles Harbor following the towed underwater video survey. SVPS photography provides a cross-sectional photograph of surface and near-surface sediment. An area 20 centimeters (cm) high by 14 cm wide is captured in this profile and recorded as a 35 millimeter (mm) slide image. SVPS photography allows detailed identification of wood waste in surface sediments and mapping of the horizontal extent

Figure 2

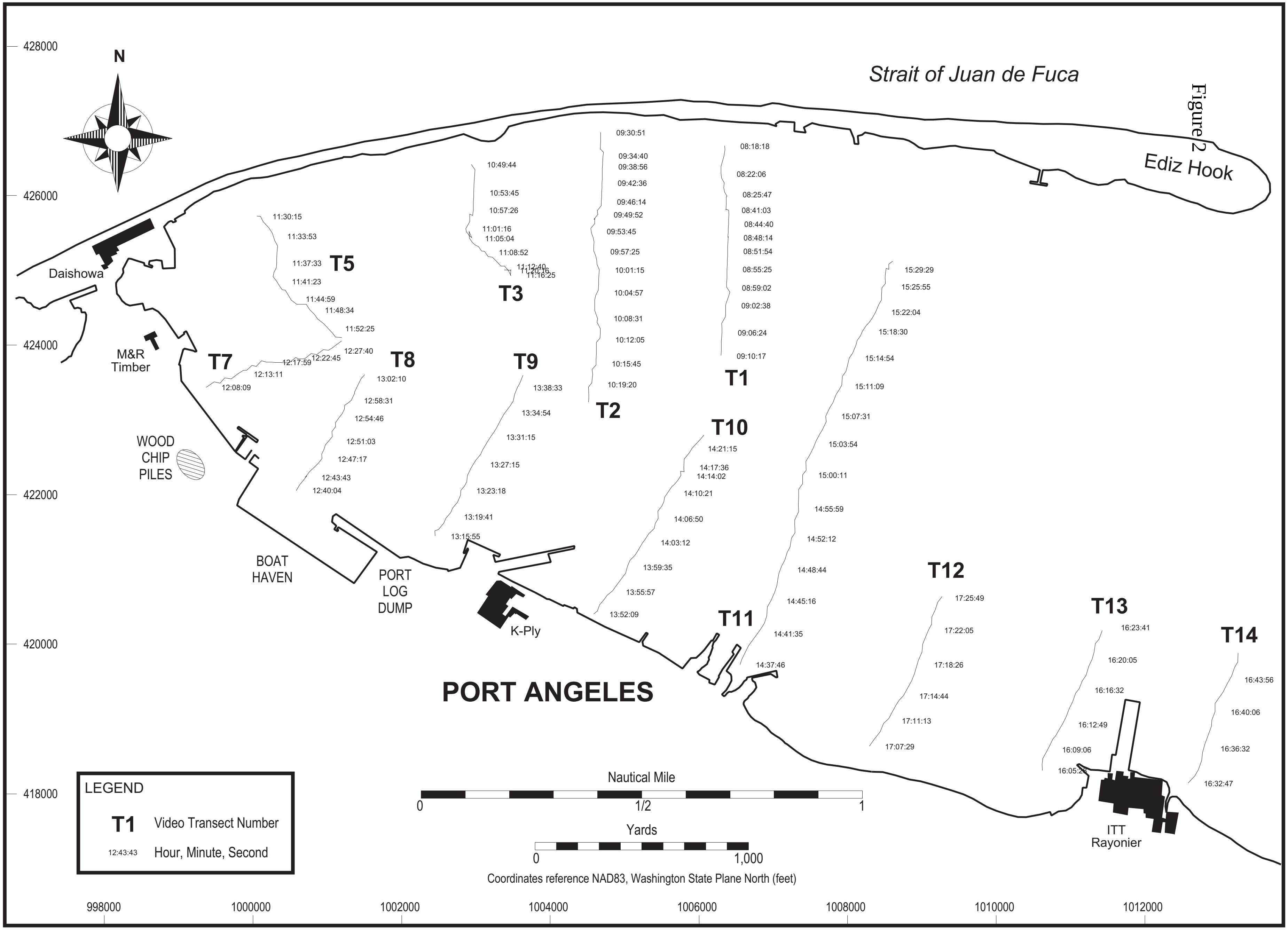


Figure 2. Towed underwater video transect locations. Port Angeles Harbor, November 3, 1998.

of wood waste accumulations at the sediment surface. Biological parameters are also measured from SVPS images to evaluate overall benthic habitat quality. A discussion of SVPS image analysis methods is provided in Section 3.0.

A total of 94 stations (37 baseline and 57 "floating" stations) were occupied during the 3-day SVPS survey (Figure 3). The baseline stations were placed in nearshore historical log storage areas where wood waste was anticipated, and in the central harbor where minimal wood waste was expected. Particular attention was made to characterize the distribution and extent of wood waste deposits. SVPS images were developed at the end of each survey day to verify successful data acquisition. Each image was inspected, and a "quick-look" assessment of environmental conditions at each station was made. Presence of wood debris and other indicators of impacted seafloor conditions were used to direct the location of the "floating" stations.

Up to three SVPS images were collected at each station. Stations 1, 49, 88, and 93 were occupied but useable profile images could not be obtained due to the presence of log debris or rocky bottom. Profile images from stations 38 and 39 were found to be overpenetrated (picture taken below the sediment-water interface) following the second SVPS survey day. These stations were re-occupied on the last survey day using less camera weight. A useable profile image was collected at station 39, but re-collected images at station 38 were also overpenetrated.

Images were collected using a Benthos model 3731 sediment profile camera (Benthos, Inc., North Falmouth, MA). The sediment profile camera consists of a wedge-shaped prism with a Plexiglas faceplate and a back mirror mounted at a 45° angle. Light is provided by an internal strobe. The mirror reflects the image of the profile of the sediment-water interface up to a 35 mm camera that is mounted horizontally on top of the prism. A diagram of SVPS camera operation is included in Appendix A.

2.3 Plan-View Photography

Plan-view underwater still photography was conducted simultaneously with SVPS photography. Plan-view images were taken using a downward looking PhotoSea underwater 35 mm camera and strobe that were mounted on the Benthos sediment profile camera frame. The plan-view camera photographs a 20 cm by 30 cm area near the front of the SVPS camera faceplate that provides a high resolution image of the sediment surface. Visual analysis of the plan-view

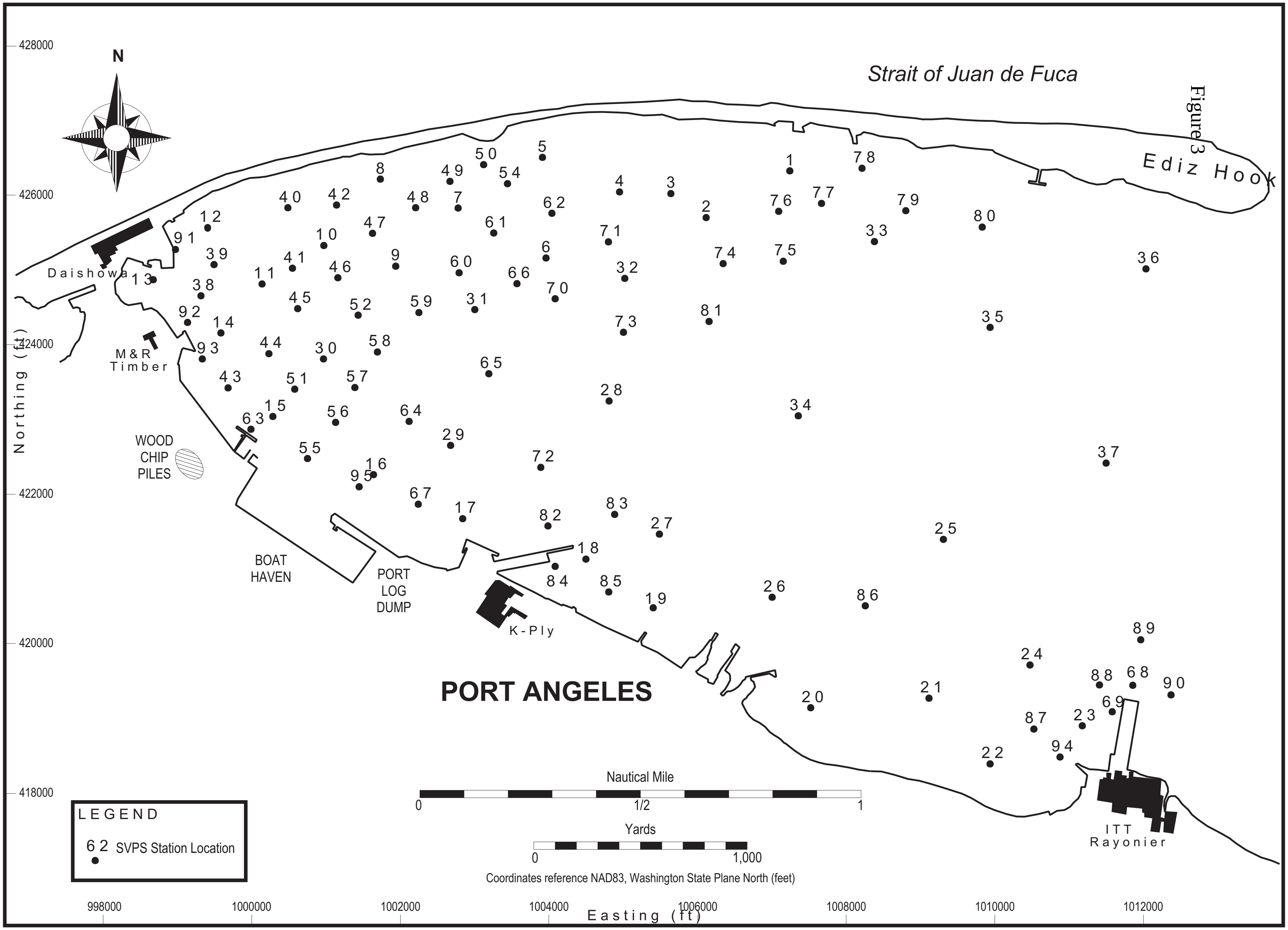


Figure 3. Port Angeles wood waste study SVPS station locations, November 4-6, 1998.

images in conjunction with SVPS images is an effective method for identifying the presence and extent of wood waste, as well as identifying other physical and biological features (e.g., sand ripples, shrimp). Results of the plan-view qualitative analysis are summarized in Appendix B.

Due to a film-advance malfunction of the plan-view camera, some plan-view images were found to overlap each other. These overlapping images were not useable in some instances. Plan-view images were not collected at stations 17, 53, 63, 72, 82, 83, and 85 due to this problem. However, useable SVPS images were collected at these stations.

2.4 Navigation

Navigation and positioning for all survey operations were accomplished using a differential global position system (DGPS) integrated with a computerized navigation system developed by SAIC. The Portable Integrated Navigation and Survey System (PINSS) provided a plan-view display to aid the helmsman and allowed the electronic recording of transect and sampling locations. The 12-channel MX400 DGPS receiver utilized U.S. Coast Guard differential corrections which provided positional accuracy of ± 3 meters in real-time. Geographic coordinates for all sampling locations are provided in Appendix B.

3.0 SVPS IMAGE ANALYSIS

SAIC has developed a standardized and formalized technique called REMOTS® (Remote Ecological Monitoring of the Seafloor) for SVPS image collection, analysis, and interpretation. Physical and biological parameters are measured directly from the SVPS color slides using a video digitizer and computer image analysis system. The image analysis system can measure up to 256 different tonal color scales, so subtle features can be accurately digitized and measured. The image analysis software allows the measurement and storage of data from up to 21 different parameters for each image.

A total of 110 Port Angeles SVPS images underwent full computer image analysis. The images included one image each from 90 stations, plus a second image from 19 (21%) of the stations to characterize small-scale (i.e., within-station) spatial variability in the measured parameters. A summary of image analysis results is provided in Appendix B. Three interactive CD-ROMs containing computer image analysis results and scanned SVPS and plan-view images will be submitted as part of the final report. The primary REMOTS® parameters used to address the Port Angeles wood waste study objectives include presence and thickness of wood waste, the apparent redox potential discontinuity depth, infaunal successional stage, presence of methane, evidence of apparent low dissolved oxygen conditions, and calculation of the organism-sediment index. A description of each parameter is described below.

3.1 Presence and Thickness of Wood Waste

Wood waste identified in SVPS images was digitized using the computer image analysis system, measured to scale, and divided by the prism window width to obtain a mean thickness of wood waste. Stations where wood waste thickness was greater than the length of the prism faceplate (20 cm) were identified as greater than the SVPS penetration limit. Due to the nature of some of the wood waste (e.g., scattered wood particles mixed in the ambient sediments) it was not always possible to distinctly measure the thickness of wood waste accumulation. In these instances, the nature of the wood waste was described, but a thickness measurement of wood waste was not calculated.

3.2 Depth of the Apparent Redox Potential Discontinuity

In fine-grained coastal areas where there is oxygen in the overlying water column, the near-surface sediment will have a higher optical reflectance (i.e., lighter color) than hypoxic or anoxic sediment underlying it. This is because the oxidized surface sediment contains ferric hydroxide (an olive color when associated with organic particles), while the hydrogen sulfide sediments below this oxygenated layer are gray to black. The boundary between the light-colored ferric hydroxide surface sediment and underlying darker-colored (gray to black) sediment is called the apparent Redox Potential Discontinuity (RPD). In general, the depth of the actual RPD is shallower than the depth of the apparent RPD because bioturbating organisms mix ferric hydroxide-coated particles downward in the sediment column. As a result, the apparent RPD depth provides an estimate of the degree of biogenic sediment mixing.

The area of the aerobic sediment was determined from the SVPS images by density slicing its unique reflectance value. Areas of anomalous high reflectance, such as shell/shell fragments and bacterial mats, were taken into account in determining the apparent RPD. The oxidized area was then digitized, measured to scale, and divided by the prism window width to obtain a mean depth for the apparent RPD. The apparent RPD is a sensitive indicator of infaunal succession, sediment bioturbation activity, and sediment oxygen demand. Areas impacted with abundant wood waste generally exhibit shallow or no apparent RPD depths.

3.3 Infaunal Successional Stage

The mapping of infaunal successional stages (the functional types of infaunal organisms) from SVPS images is based on the theory that organism-sediment interactions follow a predictable sequence after a major seafloor disturbance. In shallow water environments, infaunal succession following a major seafloor disturbance initially involves pioneering populations (Primary or Stage I succession) of very small organisms that live at, or near, the sediment-water interface (Pearson and Rosenberg, 1978; Rhoads and Germano, 1986).

In the absence of further disturbance, these early successional assemblages are eventually replaced by infaunal deposit feeders; the start of this “infaunalization” process is designated as Stage II. Large, deep-burrowing infauna, or Stage III taxa, represent a high-order successional stage typically found in areas of low disturbance. The presence of Stage III feeding voids indicate the presence of Stage III organisms. Figure 4 illustrates an idealized infaunal successional sequence following a disturbance.

3.4 High Sediment Oxygen Demand / Presence of Methane

Areas with low sediment oxygen conditions, or high sediment oxygen demand (SOD), can occur when the bottom sediment experiences severe organic loading. For example, deposition of the fine fraction of wood waste (pulp) can form a “fiber blanket” at the sediment-water interface, and dense populations of sulfate-reducing bacteria can populate this fiber blanket. Such a surface has a high SOD and a thin or non-existent apparent RPD within the sediment column. Macrofaunal colonization can range from azoic to dominance by low diversity opportunistic polychaetes (i.e., Stage I infaunal succession). When sulfate is used up, methane gas may then accumulate within the bottom sediments (observed as bubbles in SVPS images).

Areas with shallow or no RPD depths, low diversity or azoic infaunal colonization, highly reduced underlying sediment (dark gray to black in color), and the presence of methane gas bubbles in the sediment are indicative of organic loading and high sediment oxygen demand.

3.5 Organism-Sediment Index

The Organism-Sediment Index (OSI) provides a measure of benthic habitat quality in shallow water environments based on dissolved oxygen conditions, depth of the apparent RPD, infaunal successional stage, and presence or absence of sedimentary methane measured during REMOTS® image analysis (Rhoads and Germano, 1986). The OSI is a numerical index ranging from -10 to +11. The lowest value is given to bottom sediments with low or no dissolved oxygen in the overlying bottom water, no apparent macrofaunal life, and methane gas present in the sediment. High OSI values are given to aerobic bottom sediments with a deep apparent RPD, mature macrofaunal community, and no methane gas. The numerical values and ranges used in calculating the OSI are provided in Table 1. Previous SVPS surveys conducted in various coastal regions by SAIC (e.g. Puget Sound, Long Island Sound, Chesapeake Bay, and the Florida and Louisiana coasts) have shown that OSI values between +7 and +11 are typical of natural, undisturbed sediments. OSI values less than +6 indicate a “stressed” or disturbed benthic environment and values less than 0 indicate degraded benthic habitat.

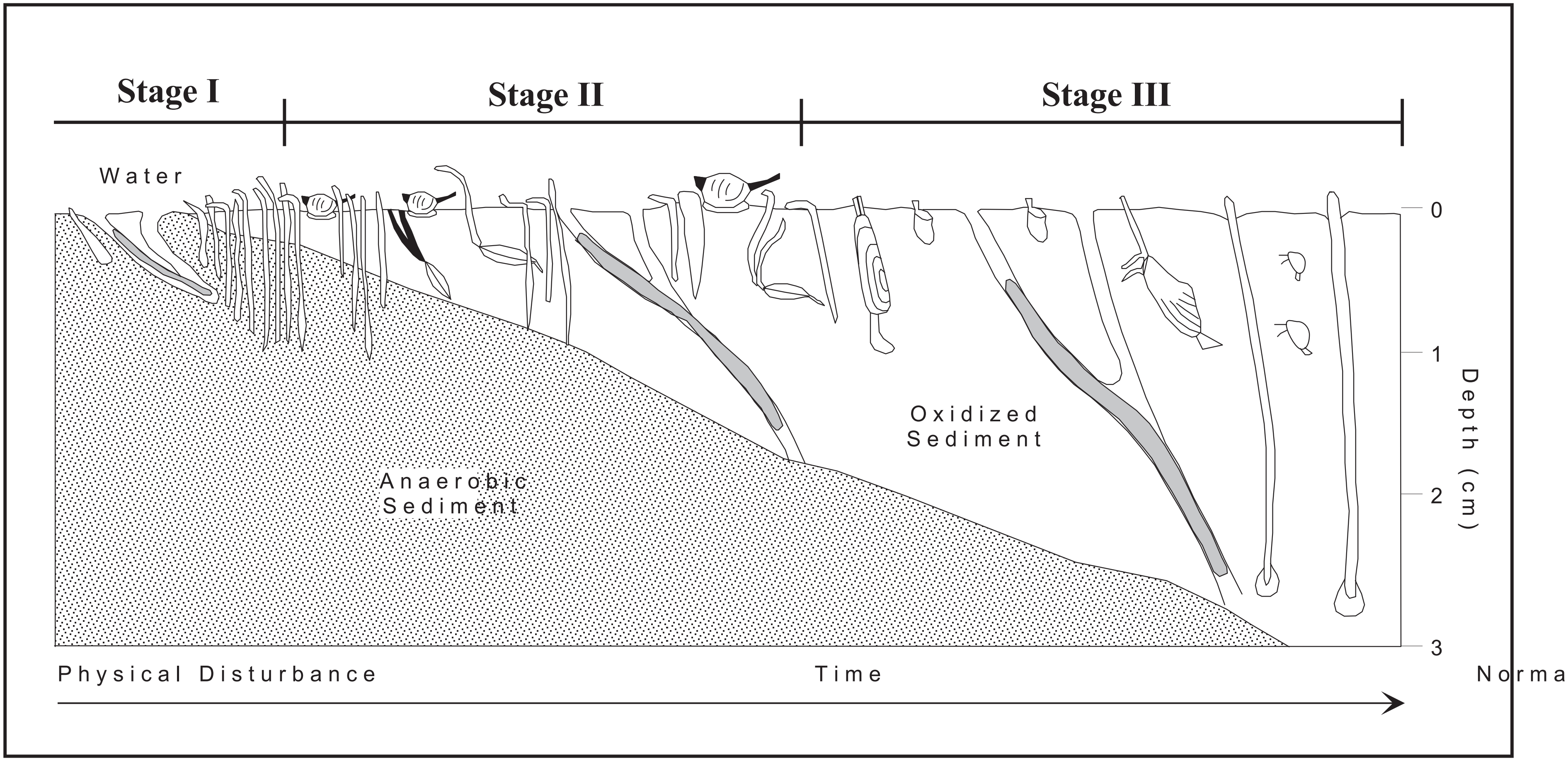


Figure 4. Development of infaunal successional stages over time following a physical disturbance. This figure is taken from Rhodes and Germano (1986) which was modified from Pearson and Rosenberg (1978).

Table 1. Calculation of the Organism-Sediment Index.

Choose One Value:

Mean RPD Depth Classes	Index Value
0.00 cm	0
> 0 - 0.75 cm	1
0.76 - 1.50 cm	2
1.51 - 2.25 cm	3
2.26 - 3.00 cm	4
3.01 - 3.75 cm	5
> 3.75 cm	6

Choose One Value:

Successional Stage	Index Value
Azoic	- 4
Stage I	1
Stage I - II	2
Stage II	3
Stage II - III	4
Stage III	5
Stage I on III	5
Stage II on III	5

Choose One or Both if Appropriate:

Chemical Parameters	Index Value
Methane Present	- 2
No/Low Dissolved Oxygen*	- 4

Organism-Sediment Index = Range: - 10 + 11

* No/low dissolved oxygen is based on the imaged evidence of reduced, low reflectance (i.e., high oxygen demand) sediment at the sediment-water interface. It is not a chemical measurement using Winkler titration or polargraphic electrode.

4.0 RESULTS

Results from the towed underwater video, SVPS photography, and plan-view underwater still photography were used to address the six objectives of the Port Angeles Harbor wood waste study:

1. Map the horizontal extent of wood waste accumulations
2. Measure the thickness of the accumulations
3. Describe the wood waste encountered
4. Measure the depth of the apparent redox potential discontinuity
5. Identify areas with potential for high sediment oxygen demand
6. Evaluate the health of the benthic macroinvertebrate community

4.1 Distribution of Wood Waste

Identification and mapping of wood waste in Port Angeles Harbor (Objectives 1 and 3) were conducted using a combination of towed underwater video, SVPS photography, and plan-view photography. SVPS photography was used to measure the thickness of wood waste accumulations (Objective 2).

4.1.1 Towed Underwater Video

Towed underwater video was used as a reconnaissance tool to determine preliminary boundaries of wood waste accumulation and guide the placement of SVPS and plan-view station locations. Towed video also provided identification of large wood waste (e.g., submerged logs) which may not be photographed using SVPS or plan-view photography.

Visual observations of wood waste made during the Port Angeles Harbor towed underwater video survey are presented in Figure 5. Abundant wood debris including logs and large bark/wood fragments was generally observed in active and historical log booming grounds. Wood debris in the active north harbor log booming grounds appears to be “fresh” (recently deposited) while the older or less active log booming areas (booming grounds near K-Ply, former ITT Rayonier grounds, and log dump grounds) contained generally older, decomposing, or bio-fouled wood deposits. Size and abundance of wood debris decreased offshore from the booming grounds.

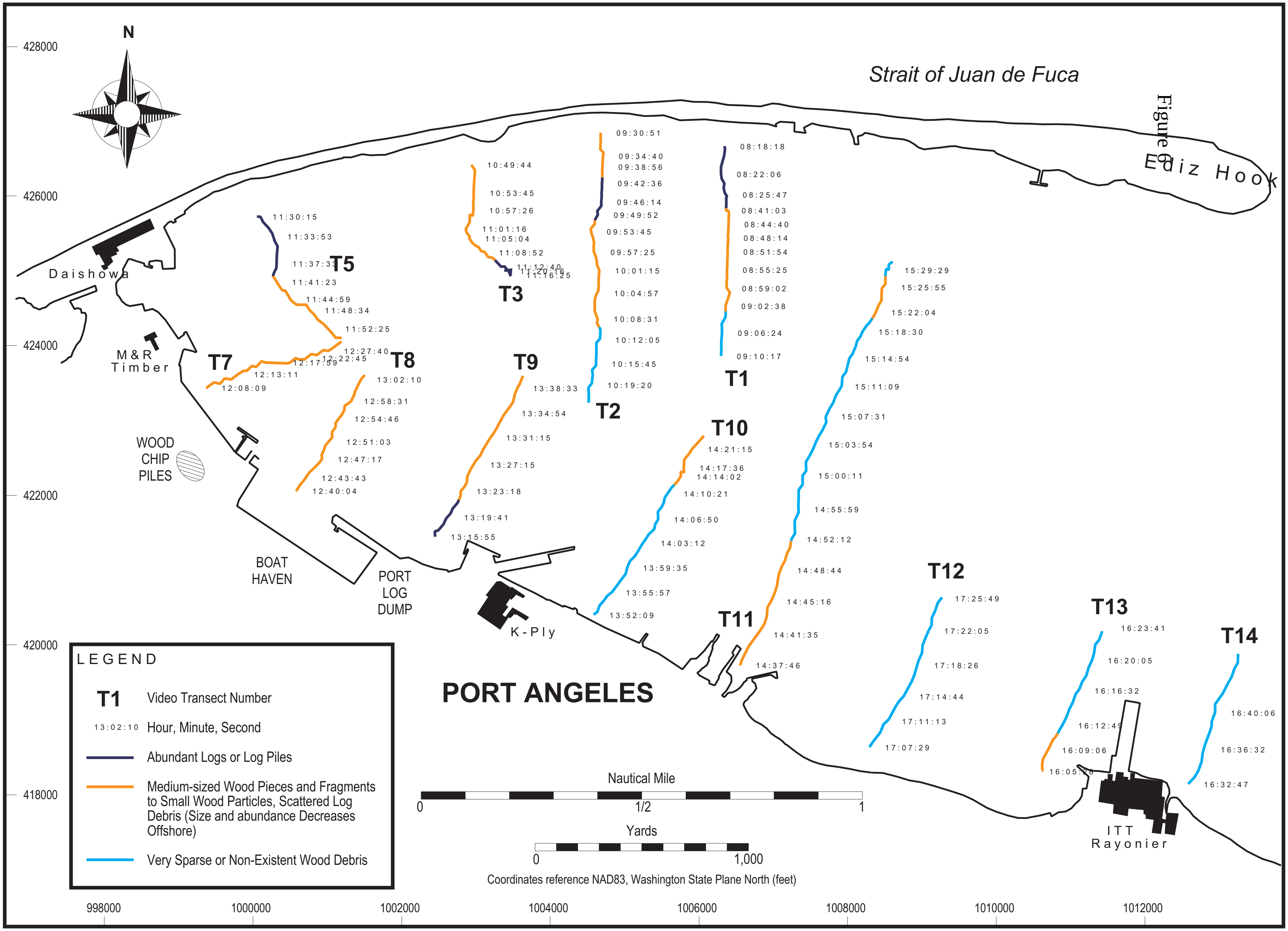


Figure 5. Wood waste identification in Port Angeles Harbor using towed underwater video.

Wood debris ranged from log-sized debris (meters), medium size wood pieces and fragments (10's of centimeters), to small wood particles (millimeters to centimeters). Wood debris was very sparse or non-existent in the central and outer harbor.

Large piles of "fresh" submerged logs were observed in the log booming grounds along the northern portion of the harbor. The logs were seen along transects T1, T2, and T3 at water depths of 100 to 150 feet. It is likely that these logs were lost from barges moored in the booming grounds. It was reported that two barge loads of hemlock were lost when the barges listed during storms earlier this year. Due to the depth of water, divers could not salvage the logs. A bathymetry (depth) map of Port Angeles Harbor is included in Appendix A.

4.1.2 SVPS and Plan-View Photography

SVPS photography provided detailed identification of wood waste types, the horizontal extent of wood waste deposits, and the measured thickness of accumulation. Sediment plan-view photography provided qualitative observations for wood waste identification and distribution. Figure 6 presents estimates of the horizontal distribution and measured accumulations of wood waste in Port Angeles Harbor, based on SVPS and plan-view photography.

Five general categories of wood waste types were identified:

- Logs or large wood pieces
- Small wood and/or bark chips (wood chips)
- Very fine wood particles and/or fibers (wood pulp)
- Trace to sparse wood pulp/chips mixed within the sediment column
- Sparse, scattered wood pieces on top of the sediment surface

Measurement of wood waste accumulations was made when discreet layers of wood chips or wood pulp were present. Areas showing logs or large wood pieces, trace to sparse wood pulp mixed within the sediment column ("MX" designation), and scattered wood pieces on the sediment surface ("SC" designation) were identified, but distinct measurements of wood waste accumulation were not possible under these conditions.

The greatest accumulation of wood waste was observed in the north and west portions of the harbor, in the active log booming grounds and near the Daishowa facility (Figure 6). This area covers approximately 400 acres (0.6 square miles) of harbor bottom. Wood waste consisted of discreet wood/pulp layers, wood pulp mixed within the sediment column (MX), and scattered wood pieces on the sediment surface (SC). The highest measurable amount of wood waste was at station 91 (next to Daishowa), where >21 cm of wood pulp accumulation was measured (Figure 7). Profile and plan-view images showing "MX" and "SC" wood waste conditions are provided in Figures 8 and 9. Wood waste was also identified near the log dumping grounds (approximately 30 acres) and the former ITT Rayonier booming grounds (approximately 55 acres). Abundant wood chip accumulations were measured at stations 23 and 94 near the ITT Rayonier facility (Figure 10).

At stations 30, 45, 51, 52, and 57 in the western central portion of Port Angeles Harbor, a layer of wood pulp was found buried under 6 to 8 cm of ambient silt (Figure 7). The wood pulp layer measures from 5.1 cm thick at station 57 to >10.1 cm at station 45, and covers an area of approximately 35 acres (see Figure 6). Assuming a conservative thickness of 5.1 cm, the wood pulp layer represents approximately 9,500 cubic yards of wood pulp. However, the subsurface layer of wood pulp does not appear to have adverse impacts to the benthic infaunal community. The profile images at these locations show well-developed RPD depths and feeding voids in the overlying ambient silt layer, and the presence of polychaetes within the wood pulp layer (Figure 7, image 52/B).

At stations 9, 12, 38, and 39, where a thin layer of wood pulp was measured at the sediment surface, the presence and growth of sulfur-reducing bacteria has created a membrane or bacterial mat (Figures 11 and 12). Presence of bacterial mats is indicative of high labile organic carbon and low dissolved oxygen conditions (see discussion in Section 5.3).

At three stations (19, 63, and 67) along the southwest shoreline, possible creosote and/or oil was observed in the SVPS images.

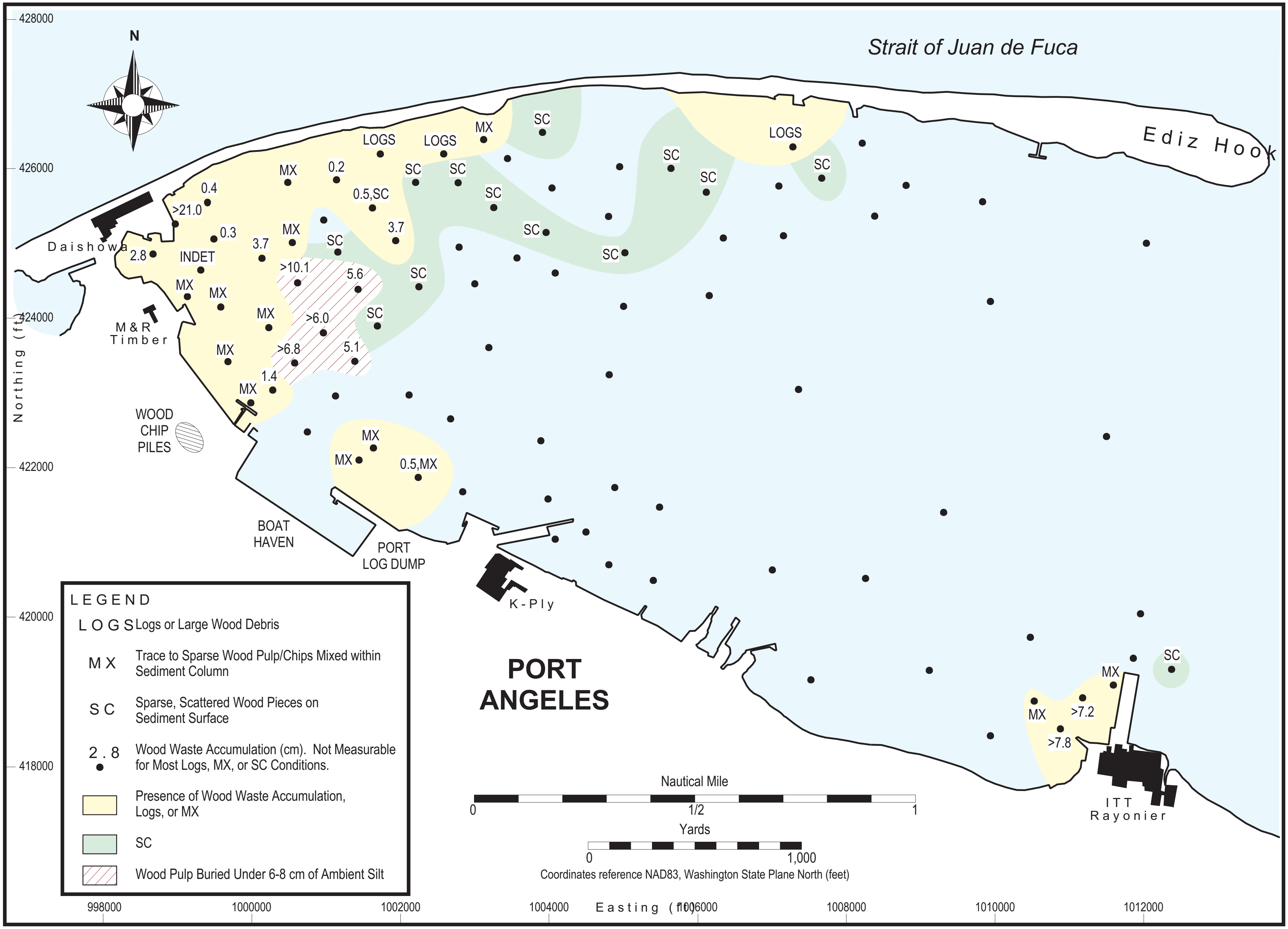


Figure 6. Wood waste distribution and accumulation in Port Angeles Harbor based on SVPS and plan-view photography.

91/A 52/B

SVPS
Scale
2cm

Figure 7. SVPS images from stations 91 (replicate A) and 52/B in Port Angeles Harbor. Station 91 is located near the Daishowa loading dock and shows abundant wood pulp accumulation greater than camera prism penetration. Overpenetration indicates high water content and a high sedimentation rate. Silt is mixed into the upper portions of the wood fabric. Station 52 located in the western central portion of the harbor shows a wood pulp layer (5.2 cm) buried under 7.9 cm of ambient sediment. A feeding void (arrow) is present and a polychaete is feeding within the wood pulp layer.

63/B

69/A

Scale

2cm

Figure 8. SVPS images from stations 63/B and 69/A in Port Angeles Harbor. Station 63 located near the K-Ply wood chip loading dock shows fine wood particles (pulp) mixed within the sediment column. The image shows a well-developed apparent RPD depth (3.56 cm) and a filamentous red/brown algae (bacterial mats'?) is present on the sediment surface. Station 69 located along the western pier-face of the former ITT Rayonier facility also shows wood pulp mixed within the sediment column. Two methane bubbles are present within relic feeding voids (arrows) which indicates degraded sediment conditions and potential for high sediment oxygen demand.

6/B (SVPS)

SVPS Scale

2 cm

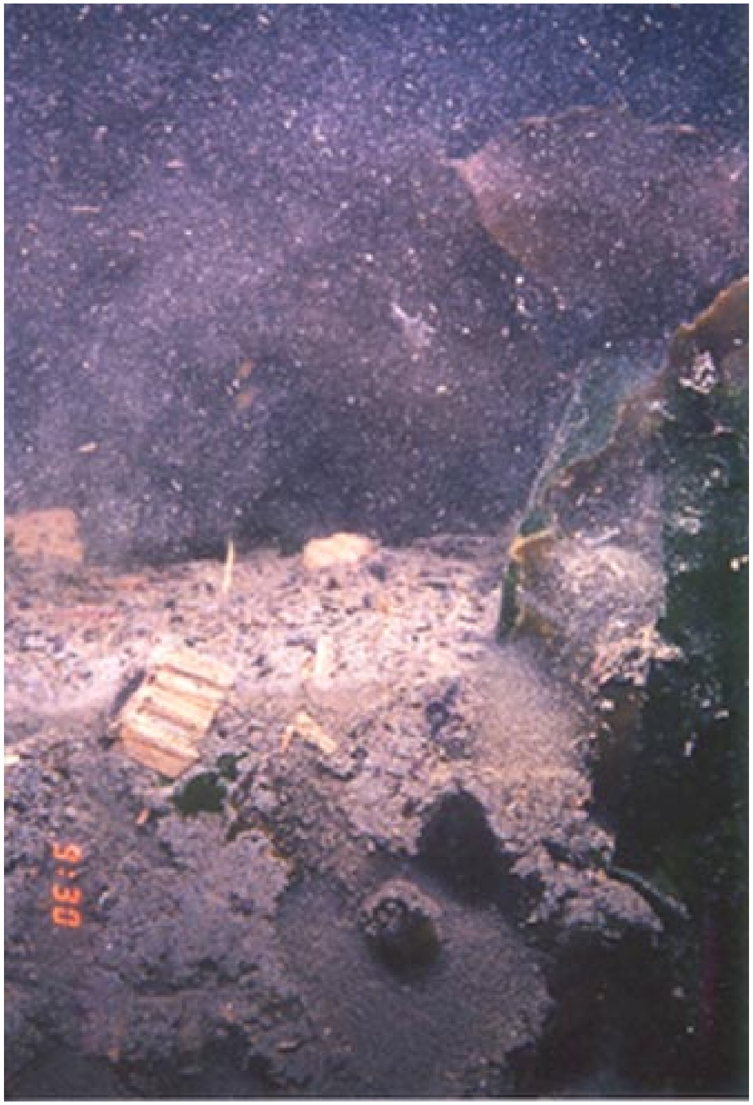
6/C (Plan-View)

Plan-View Scale

3 cm

Figure 9. SVPS and plan-view images from station 6 (north-central part of the harbor) where sparse. scattered wood debris is present on the sediment surface. The SVPS image shows healthy sediment conditions. A well-developed apparent RPD depth. feeding voids (arrows), and a possible anemone burrow are present (dotted line delimits the burrow). The plan-view image shows a piece of wood debris on the sediment surface with a shrimp seeking shelter beneath the wood debris.

23/C



94/C

Scale

2 cm

Figure 10. **SVPS** images from stations 23/C and 94/C in the log booming grounds near the former ITT Rayonier facility. Station 23 shows abundant wood chips and fibers mixed in the surface sediments. Green algae (*Ulva* and/or *Enteromorpha*) on the right side of the image has been dragged down into the sediment by the camera prism. Station 94 shows a pile of wood chips and fragments (>7.8 cm). Underlying sediments are not visible in the image.

9/c (SVPS)

SVPS Scale

2cm

9/A (Plan-View)

Plan-View Scale

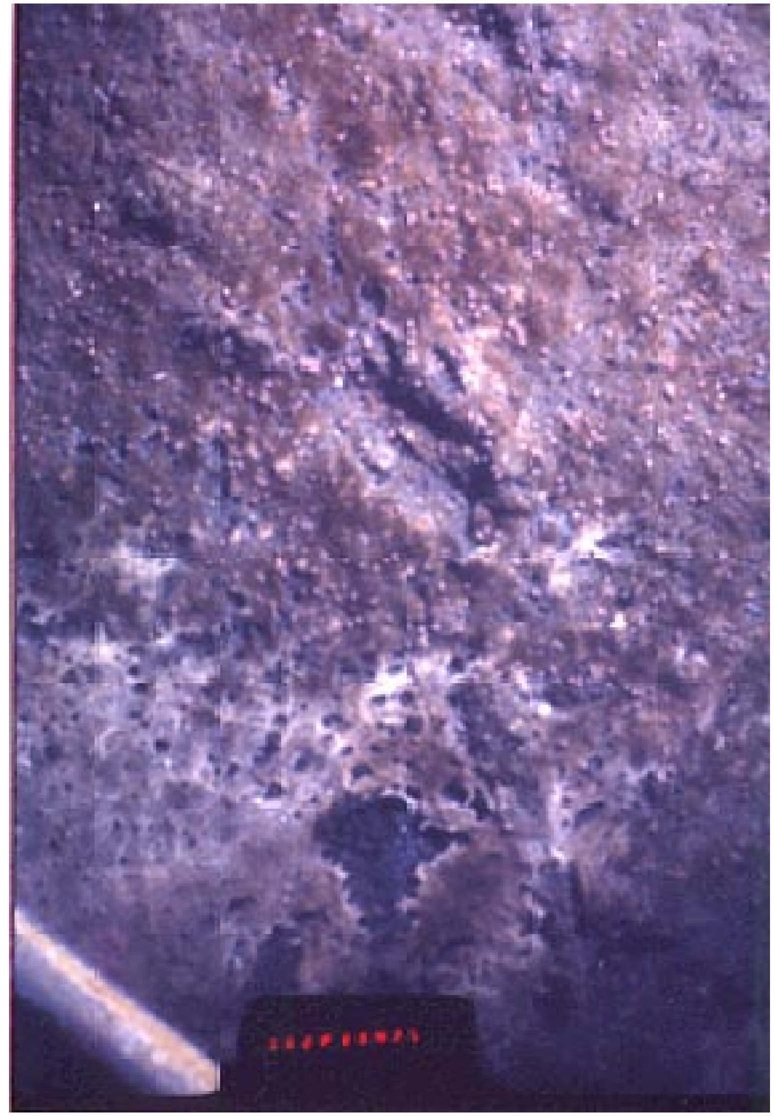
3 cm

Figure 11. SVPS and plan-view images from station 9 (in log booming grounds in north-central part of the harbor) showing the presence of a wood fiber layer. Dense populations of sulfate-reducing bacteria have created a "bacterial mat" or membrane on the sediment surface (white fibrous material in the SVPS and plan-view images). Formation of these bacterial mats occurs in anaerobic conditions. Sediments underlying the bacterial mat (approximately 3.7 cm thick) are black and sulfidic.

12/A (SVPS)

SVPS
Scale
2 cm

12/A (Plan-View)



Plan-View
Scale
3 cm

Figure 12. SVPS and plan-view images from station 12 (in log booming grounds just east of Daishowa) showing the presence of a wood fiber layer. Dense populations of sulfate-reducing bacteria have created a thin "bacterial mat" or membrane on the sediment surface (white fibrous material in the SVPS image). Notice the ventral "fringes" of filaments in the bacterial mats (black arrow). A methane bubble is also present at depth in a relic feeding void (white arrow). The bacterial mat surface has high sediment oxygen demand. As the bacteria use up sulfate, sedimentary methane can accumulate. The plan-view image shows the fibrous, membrane-like appearance of the bacterial mat. The bulb-like features on the surface may be fusiform rods related to a different type of bacterial growth.

Based on results of the towed underwater video survey, it is apparent that wood debris is present outside of the wood waste perimeter measured using SVPS and plan-view photography (compare Figures 5 and 6). However, the lack of visual evidence in the SVPS and plan-view images suggests that the amount of wood debris is low in these areas and is having little impact on the benthic habitat. The distribution of wood debris is patchy, so that it appears in the wider-ranging video survey, but not in all of the very localized SVPS and plan-view photographs.

4.2 Depth of the Apparent RPD

SVPS photography was used to measure the depth of the apparent RPD (Objective 4). The depth of the apparent RPD provides an estimate of the degree of oxygenation in the sediment column as well as the degree of biogenic sediment mixing.

Mean apparent RPD depths in Port Angeles Harbor had a major mode around 2.25 cm (Figure 13 inset). Greater apparent RPD depths were found in open-water areas of the central harbor (Figures 13 and 14), where wood waste accumulation generally was low or minimal and where there is assumed to be a higher rate of tidal exchange compared to nearshore shallow areas. Although scattered wood pieces were observed at the sediment surface at Station 2, this station in the northern central portion of the harbor had the greatest apparent RPD depth of 5.59 cm. The shallowest RPD depths generally were found at stations located in both active and historical log booming grounds; areas with apparent RPD depths less than 1.00 cm are highlighted in Figure 13. Note that indeterminate RPD values were recorded at several stations near the ITT Rayonier facility due to poor camera prism penetration. Water depths are shallow in this region (10 to 15 feet deep) and the bottom consists of a hard, rocky substrate.

Stations with non-existent apparent RPD depths were observed near the Daishowa facility, the log dump grounds, the booming grounds near K-Ply, and the former ITT Rayonier grounds. While there is an association between areas of active/historical log booming and shallow/non-existent RPD depths, it is important to note such RPD depths were not always associated with actual accumulations of wood waste observed on or within the sediment. For example, no wood waste was observed at the stations around K-Ply (Figure 6), but apparent RPD depths in this area were very shallow. Likewise, Station 55 near the port log dump had a non-existent RPD but no observed wood waste. In general, the areas along the shoreline having shallow RPD depths, particularly in the western harbor, are also areas where water circulation within the harbor may be

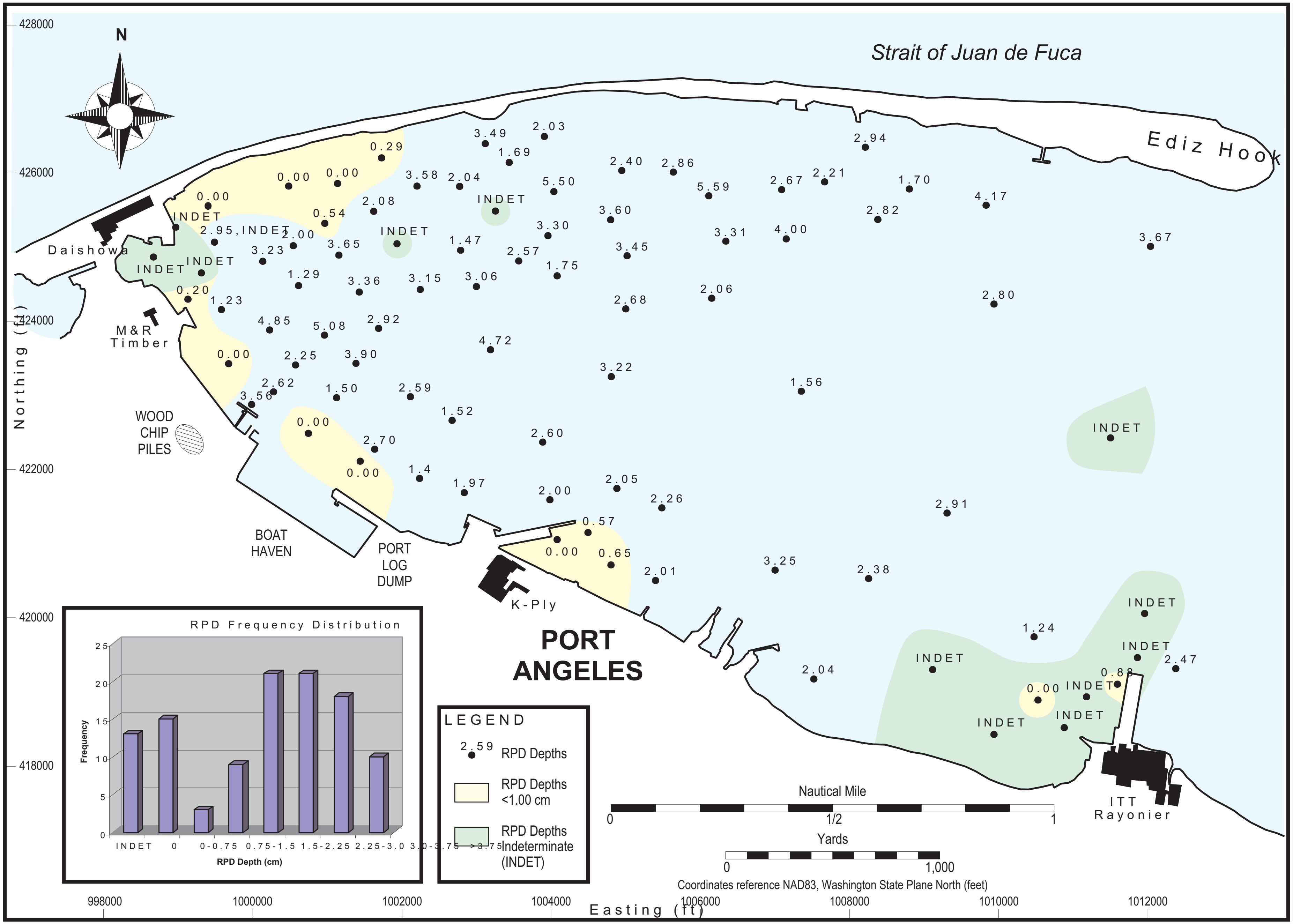


Figure 13. Distribution of the redox potential discontinuity (RPD) depth in Port Angeles Harbor.

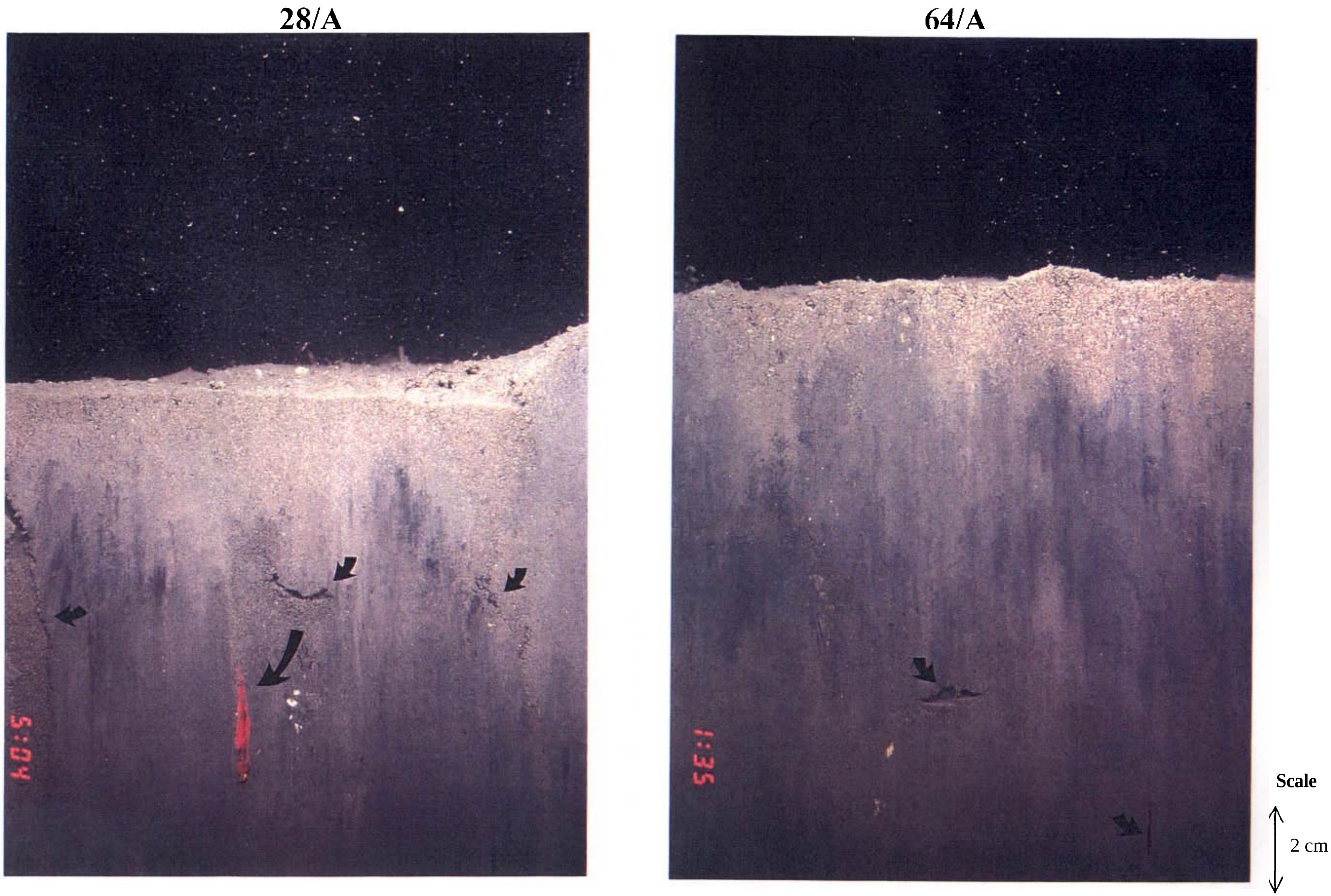


Figure 14. SVPS images from stations 28/A and 64/A in the central harbor showing minimal pulp impact. Station 28 shows Stage I tube worms on the sediment surface and a polychaete worm at depth (large arrow). Stage III feeding voids and a possible burrow (small arrows) are present as well as a deep apparent RPD (3.22 cm). Station 64 provides a good reference for undisturbed bottom conditions in Port Angeles Harbor. The image shows a well-developed apparent *RPD* depth and the presence of a Stage III feeding void and polychaete (arrows) at depth.

minimal. Accumulation of wood waste within or on the sediment, poor water circulation, and other potential sources of organic enrichment (e.g., surface runoff) may all contribute in varying degrees and combinations to the low sediment oxygen levels observed at the nearshore REMOTS® stations.

4.3 High Sediment Oxygen Demand

SVPS and plan-view photography are used to identify areas with potential for high sediment oxygen demand (Objective 5). Areas with apparent high sediment oxygen demand (SOD) or with potential for high SOD in Port Angeles Harbor are identified in Figure 15. Apparent high SOD designations were given to stations with shallow or no RPD depths, low diversity or azoic infaunal colonization, highly reduced sulfidic sediment (dark gray to black in color), and the presence of methane gas bubbles in the sediment. Sedimentary methane bubbles were photographed at stations 69 and 12 (Figures 8 and 12, respectively). Presence of bacterial mats on the sediment surface also indicates low dissolved oxygen conditions (see Section 5.3).

Areas with shallow or no RPD depths indicate poor oxygenation in the sediment column, and could lead to low dissolved oxygen conditions. Therefore, areas with apparent RPD depths less than 1.00 cm were identified as areas with potential for high SOD. Station 39 showed an RPD of 2.95 cm in one SVPS image, and an indeterminate RPD and apparently anoxic mud in another. Therefore, this station is considered to have a potentially high SOD.

4.4 Benthic Community

The health of the benthic macroinvertebrate community (Objective 6) is evaluated using SVPS and plan-view photography. Depth of the apparent RPD (discussed in Section 4.2) is an important parameter in assessing the health of the benthic infaunal community. Also important are the determination of infaunal successional stage, and the calculation of the Organism-Sediment Index (OSI).

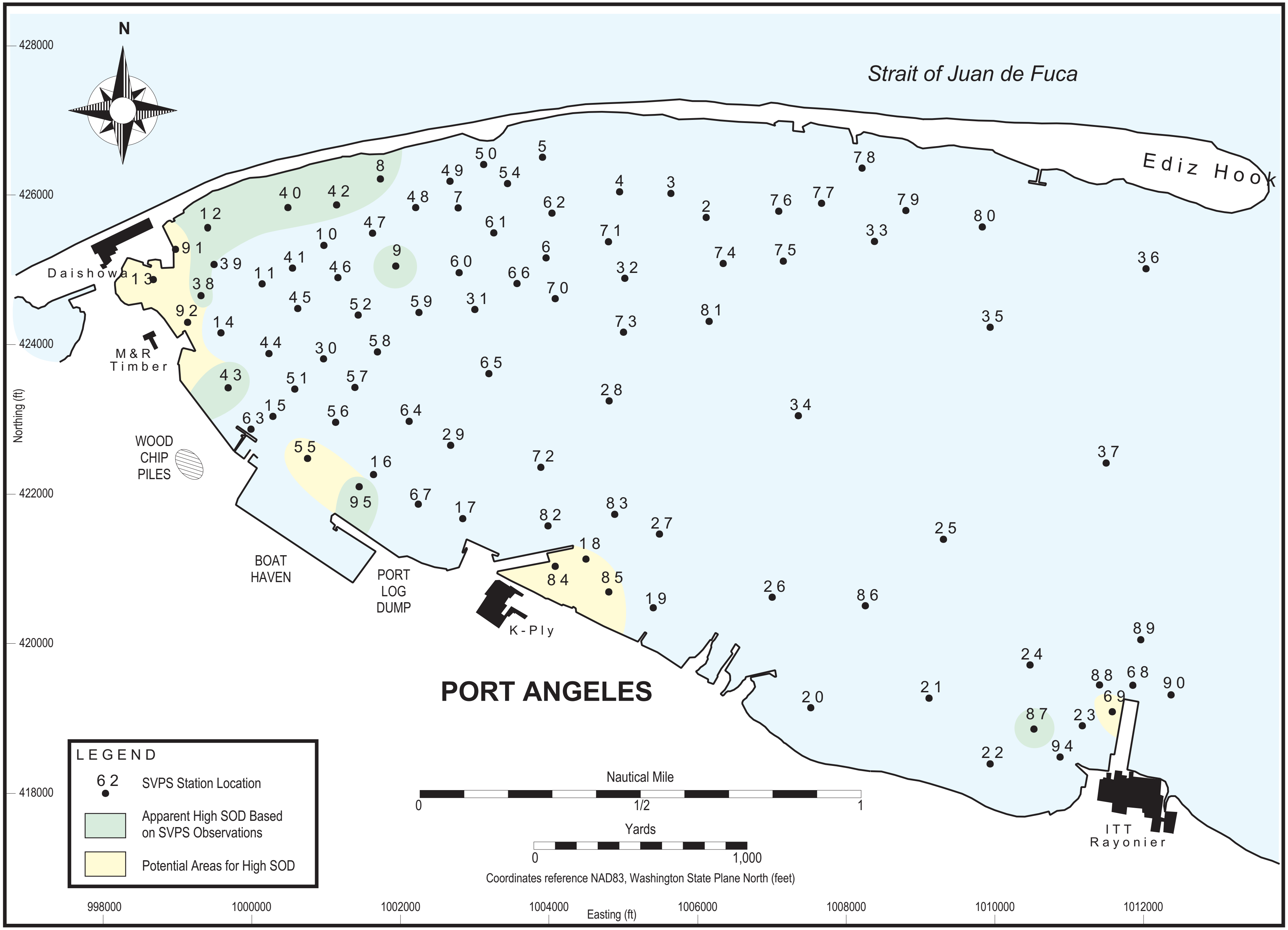


Figure 15. Stations with apparent or with potential high sediment oxygen demand (SOD) in Port Angeles Harbor.

4.4.1 Infaunal Successional Stage

The mapping of infaunal successional stages (the functional types of infaunal organisms) in Port Angeles Harbor is presented in Figure 16. The infaunal community in most areas of Port Angeles Harbor consists of small surface feeding or filtering Stage I organisms and larger head-down deposit feeders (Stage III). Stage III assemblages were present in most offshore areas of the central harbor (Figure 16). Areas with only pioneering or Stage I succession are generally associated with the log booming grounds. In addition, some nearshore stations within the western log booming areas (stations 8, 12, 13, 43, and 95) showed no evidence of benthic infaunal colonization (AZOIC). Infaunal successional stage could not be determined at several stations near the ITT Rayonier facility due to the hard, rocky substrate and poor camera prism penetration. For some of the stations where two SVPS images were analyzed, different stages were identified in the two images, indicating small-scale patchiness in benthic conditions.

4.4.2 Organism-Sediment Index

The Organism-Sediment Index (OSI) is a sensitive metric for measuring benthic habitat quality and assessing stages of organic enrichment in shallow water environments. The OSI is calculated based on dissolved oxygen conditions, depth of the apparent RPD, infaunal successional stage, and presence or absence of sedimentary methane.

OSI values in Port Angeles Harbor had a major mode of +9 (Figure 17 inset). The majority of OSI values in the central harbor were between +7 and +11, indicating healthy and undisturbed benthic conditions. Areas with OSI values less than +6 (stressed or disturbed conditions) were generally found in the log booming grounds. Degraded benthic habitat (OSI less than zero) was observed at stations 8, 12, 40, 43, and 95. Because the OSI is calculated using apparent RPD depths and successional stages, indeterminate apparent RPD depths and/or successional stages lead to indeterminate OSI values. Several OSI values near the ITT Rayonier facility were indeterminate because either the RPD depth or successional stage, or both, were indeterminate. At two stations near the ITT Rayonier facility where apparent RPD depths could be measured, they were shallow (less than 1.0 cm; Figure 13). At station 13 next to the Daishowa facility, the OSI value was indeterminate due to an indeterminate RPD, but an “azoic” successional designation suggested a degraded benthic habitat quality.

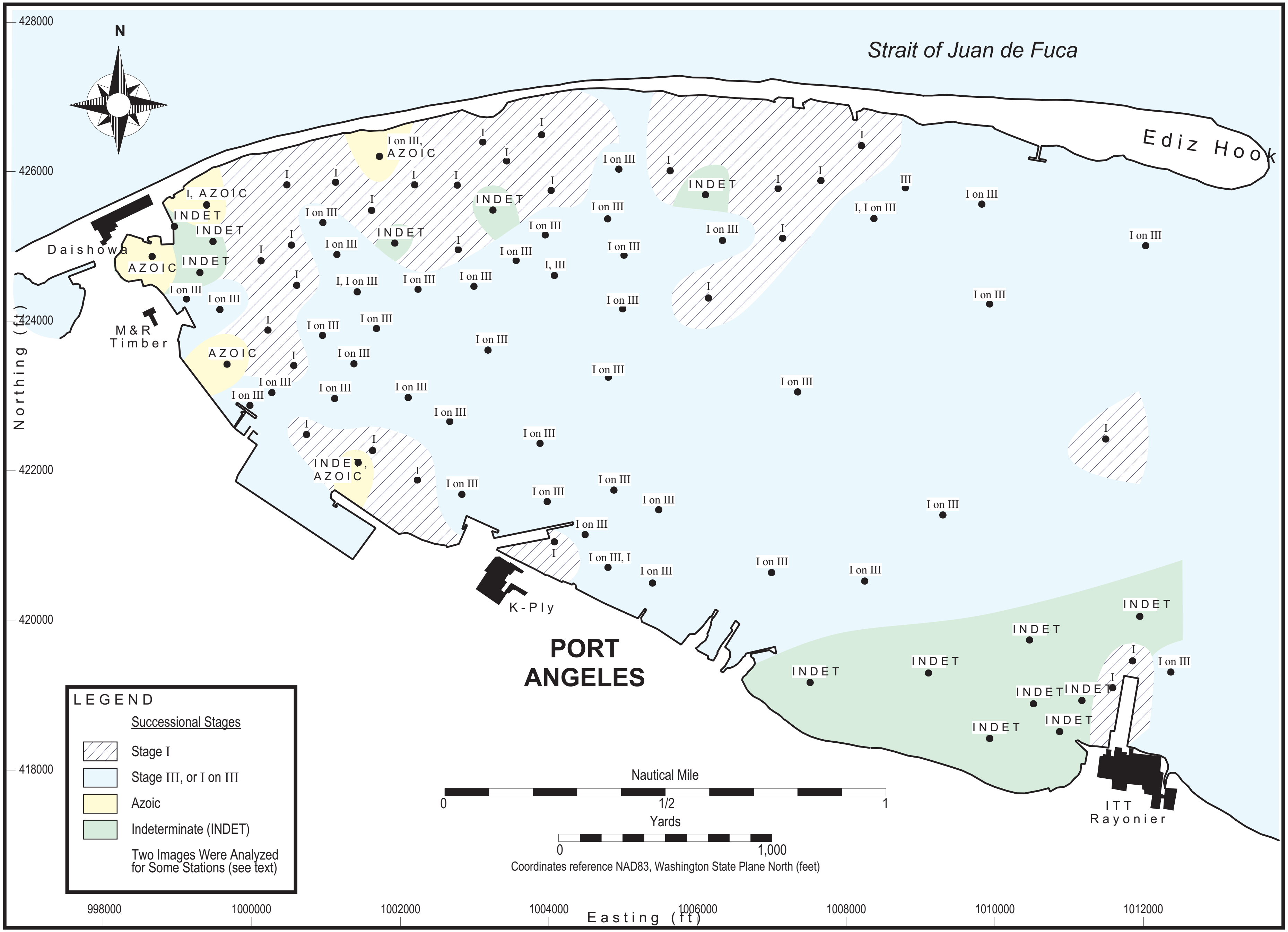


Figure 16. Distribution of infaunal successional stage in Port Angeles Harbor.

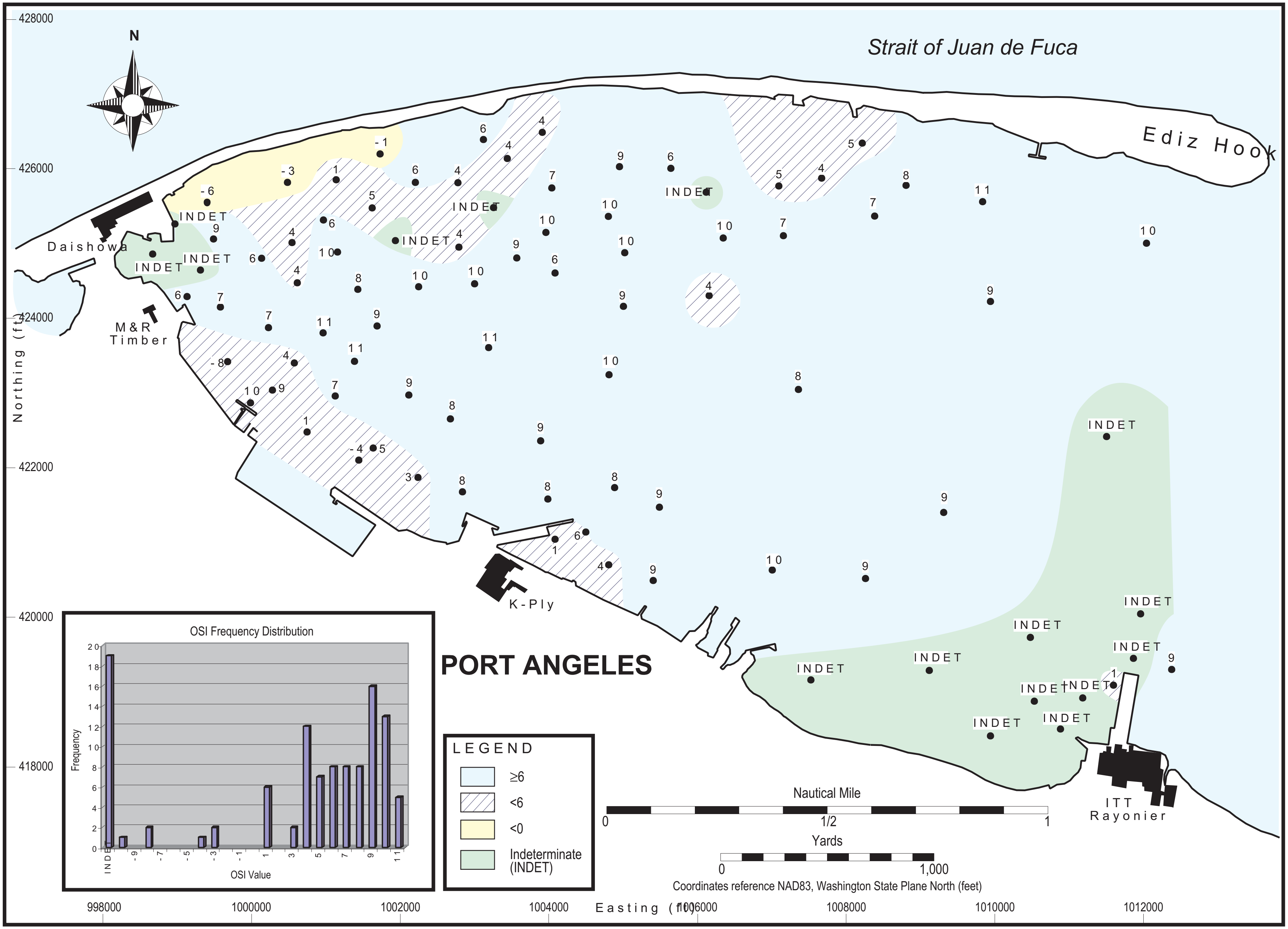


Figure 17. Distribution of organism-sediment indices (OSI) in Port Angeles Harbor.

5.0 DISCUSSION

5.1 Wood Waste Distribution

Abundant wood debris including logs and large bark/wood fragments was generally observed in the log booming grounds. These areas included the log booming areas in the northern harbor, near the Daishowa and M&R Timber facilities, near the public log dump, and near the former ITT Rayonier facility. Measurable wood pulp or wood chip deposits were generally confined to these nearshore areas (Figure 6). Wood waste was observed over approximately 500 acres of the harbor bottom, with about 400 acres covered near the north and west portions of the harbor (Figure 6). The horizontal distribution of wood waste covers approximately 25 percent of the bottom of Port Angeles Harbor. Size and abundance of wood debris generally decreased offshore from the booming grounds.

A layer of wood pulp was found buried under 6 to 8 cm of ambient silt in the western central harbor (Figures 6 and 7). The subsurface wood pulp deposit covers an area of approximately 35 acres. Very little sediment is mixed within the pulp layer, suggesting that the wood pulp was deposited very rapidly on the harbor bottom. One possible explanation could be that barges loaded with wood pulp may have listed during a storm and lost their loads. Assuming a conservative thickness of 5.1 cm, the buried wood pulp layer represents approximately 9,500 cubic yards of wood pulp.

5.2 Wood Waste Impacts

Areas of the harbor bottom with no apparent wood debris have healthy sediment conditions with epibenthic organisms present on the sediment surface (Figures 14 and 18). Figure 18 shows a small flat fish present at the sediment surface at station 35 (central outer harbor). The underlying sediments have well-developed apparent RPD depths, and Stage III infaunal communities are present.

The presence of sparse, scattered wood debris on the sediment surface ("SC" designation in Figure 6) appears to have minimal impact on the health of the benthic community. At many locations with scattered wood debris, apparent RPD depths are well developed, Stage III infaunal communities are present, and epibenthic organisms are observed on the sediment surface. Figure

35/A (Plan-View)

77/A (Plan-View)

Plan-View Scale

3 cm

Figure 18. Plan-view images from stations 35/A and 77/A in northern Port Angeles Harbor. Station 35 shows the presence of a small flat fish (approximately 5 cm long) on the sediment surface along with a piece of algae debris. Wood **waste** is absent at this location. Station 77 shows the presence of a small Cancer crab (approximately 6 cm) and small fish (goby?). Sparse, scattered wood debris is present on the sediment surface in this part of the harbor.

18 shows a crab (*Cancer*) and small fish (goby?) at station 77, where sparse wood debris was observed on the sediment surface. Figure 9 shows a plan-view image at station 6 with a shrimp seeking shelter below a piece of wood debris. Similarly, a coon-striped shrimp (*Pandalus danae*) is sitting on a stick on the harbor bottom at station 47 (report cover). As long as overlying water quality is not impacted, wood debris can provide habitat for epibenthic organisms.

The value of wood debris as epibenthic habitat is also supported by towed underwater video observations (Figure 19). Rockfish (Yellowtail?) were observed in log piles in the nearshore areas of transect T1. Abundant anemones (*Metridium*) were often seen attached to submerged logs and wood debris. Abundant populations of shrimp were seen inhabiting wood debris in the deep northern portion of the harbor, in water depths of 100 to 150 feet. Crabs (*Cancer*), sea cucumbers, and seastars were also observed in association with wood debris during the towed video survey.

However, the benefits of wood debris to the epibenthic organisms can come at the expense of the benthic infaunal community. Accumulations of log piles or wood debris piles on the harbor bottom can smother the underlying sediments, eliminating the infaunal community and creating anaerobic sediment conditions. For example, stations 2, 12, 13, 43, and 95 in log booming areas in the western harbor were azoic, showing no evidence of benthic infaunal colonization.

5.3 Bacterial Mats

Accumulations of fine wood particles (i.e., pulp, wood chips) in low energy environments causes organic enrichment, leading to degradation of benthic habitat and potentially to a decline in the overlying water quality. This process appears to be occurring at some stations along the western shoreline of the harbor (see Figure 15). Bacterial mats were observed at stations 9, 12, 38 and 39, which indicate high labile organic loading and low dissolved oxygen conditions (Figure 11 and 12). Dense populations of sulfate-reducing bacteria can populate wood pulp deposits. This “fiber blanket” surface has a high SOD and a thin or non-existent apparent RPD depth within the sediment column. When sulfate is used up, methane gas may then accumulate within the bottom sediments (observed as bubbles in SVPS images). A methane bubble is present in a relict feeding void at station 12 (see Figure 12).

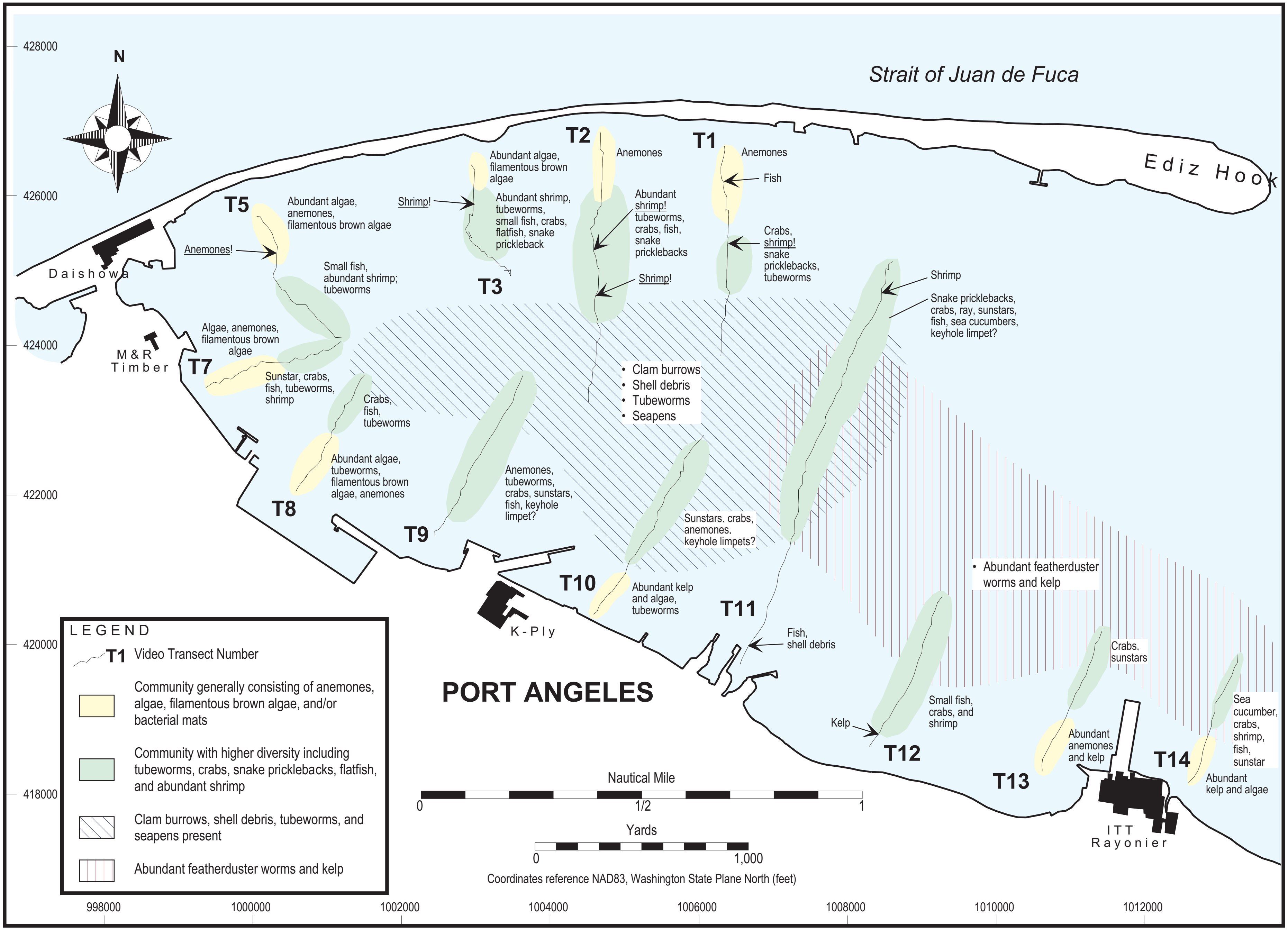


Figure 19. Epibenthic activity in Port Angeles Harbor based on towed underwater video.

Bacterial mat colonies can hinder the recovery of degraded, organically overloaded sediments. Bacterial mats act as a membrane over the underlying sediments, even if low dissolved oxygen conditions have ceased in overlying waters. The bacteria continue to feed off of the sulfate source, keeping underlying sediments anaerobic. Habitat value of this bottom type in terms of fish production is close to zero; prey are essentially non-existent and the low dissolved oxygen conditions are not tolerable by most fish species.

In-situ capping of degraded areas with clean sediment can be a potential remediation measure, provided wood waste input can be reduced or eliminated. Natural sedimentation has apparently "capped" the wood pulp deposit in the western central harbor (north of the Boat Haven). Surface sediments overlying the pulp deposit show well-developed RPD depths, feeding voids, and the presence of polychaetes feeding within the wood pulp layer (Figure 7). However, deposition of fine wood debris (pulp and wood chips) is likely regulated in part by water circulation in the harbor. The western harbor has the greatest potential for poor water circulation. Log rafting and other nearby wood-related activities also provide the greatest potential for wood waste accumulation on the harbor bottom. These two conditions have likely contributed to the degraded sediment conditions observed in the western harbor.

5.4 Organism-Sediment Index

The Organism-Sediment Index (OSI) provides a good summary metric for measuring the health of the benthic infaunal community and assessing stages of organic enrichment in Port Angeles Harbor. The OSI incorporates several of the parameters measured in this study (apparent RPD, infaunal successional stage, dissolved oxygen conditions, and sedimentary methane) into a numerical index sensitive to measuring benthic habitat quality.

OSI values in the central harbor were between +7 and +11, indicating healthy and undisturbed benthic conditions (Figure 17). Stressed or disturbed conditions (OSI values less than +6) were generally observed in the log booming grounds (Figure 17). An OSI value less than +6 reflects sediment with shallower apparent RPD depths and primary or Stage I infaunal succession. These areas are recently disturbed or in various stages of organic overloading due to wood waste deposition. Degraded benthic habitat (OSI values less than zero) was observed at stations 8, 12, 40, 43, and 95 in log booming areas in the western harbor. These areas have very shallow or non-existent RPD depths, no evidence of benthic infaunal colonization, and apparent high SOD.

Sedimentary methane and bacterial mats were also present in some of these areas. This late stage of degradation may be long lasting. Near-bottom oxygen in these areas is used up in the decay of organic matter and oxidation of reduced compounds such as methane, ammonia, and hydrogen sulfide.

6.0 CONCLUSIONS

The following conclusions can be made regarding the objectives of the Port Angeles Harbor wood waste study:

1. Map the horizontal extent of wood waste accumulations

Wood waste covers approximately 25 percent of the bottom of Port Angeles Harbor (Figure 6). Approximately 400 acres of harbor bottom is covered by wood debris in the north and west portions of the harbor, in the active log booming grounds near the Daishowa facility. Approximately 30 acres are covered near the public log dump, and approximately 55 acres are covered near the former ITT Rayonier booming grounds.

2. Measure the thickness of the accumulations

Abundant wood debris including logs and large bark/wood fragments was observed in the active and historical log booming grounds. Large piles of recently deposited logs were observed in the active log booming grounds along the northern portion of the harbor. Size and abundance of wood debris decreased offshore from the booming grounds.

Discreet measurement of wood waste thickness could only be made in areas of dense wood pulp or wood chip accumulation. Measurable wood pulp layers were observed in the northern harbor, near the Daishowa and M&R Timber facilities, near the public log dump, and near the former ITT Rayonier facility (Figure 6). The highest wood pulp accumulation (> 21cm) was measured at station 91, near the Daishowa facility.

A layer of wood pulp is buried under 6 to 8 cm of ambient silt in the western central harbor (Figures 6 and 7). The wood pulp layer measures from 5.1 cm thick at station 57 to >10.1 cm at station 45. The layer covers approximately 35 acres and represents a volume of about 9,500 cubic yards of wood pulp (wet-volume).

3. Describe the wood waste encountered

Five types of wood waste were identified on the bottom of Port Angeles Harbor:

- Logs or large wood pieces
- Small wood and/or bark chips (wood chips)
- Very fine wood particles and/or fibers (wood pulp)
- Trace to sparse wood pulp/chips mixed within the sediment column
- Sparse, scattered wood pieces on top of the sediment surface

4. Measure the depth of the apparent RPD

Mean apparent RPD depths in Port Angeles Harbor had a major mode around 2.25 cm (Figure 13). Deeper apparent RPDs were measured in areas where little or no wood waste accumulation was observed. Shallower or non-existent (i.e., zero) apparent RPD depths were associated with active and historical log booming grounds and indicate organic overloading. Stations with non-existent apparent RPD depths were observed at stations near the Daishowa facility, the public log dump grounds, the booming grounds near K-Ply, and the former ITT Rayonier grounds.

5. Identify areas with potential for high SOD

Apparent high SOD conditions exist in the western harbor near the Daishowa and M&R Timber facilities, the port log dump, the booming grounds near K-Ply, and the former ITT Rayonier grounds (Figure 15). These are areas of accumulation of fine wood waste (pulp) that is at least in part responsible for the high SOD. Other possible contributors to this condition are poor water circulation/flushing and organic loading from surface runoff. Several stations showed no apparent RPD depths and no evidence of benthic infaunal communities. Two stations showed sedimentary methane. Bacterial mats, which indicates organic enrichment and low dissolved oxygen conditions, were also observed at four stations in the western harbor.

6. Evaluate the health of the benthic macroinvertebrate community

The OSI provides a good summary metric for measuring the health of the benthic community in Port Angeles Harbor. OSI values in the central harbor were between +7 and +11 indicating healthy benthic conditions (Figure 17). High OSI values reflect deep apparent RPD depths, Stage

III infaunal communities, and low SOD. Stressed or disturbed conditions (OSI values less than +6) were generally observed in the log booming grounds. Degraded benthic habitat (OSI less than zero) was observed at stations 8, 12, 40, 43, and 95 in log booming grounds in the western harbor. Stations 8, 12, 13, 43, and 95 in these areas were azoic.

7.0 REFERENCES

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